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Survivability of an Active Protection System during Combat

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ABSTRACT

An Active Protection System (APS) consists of sensor(s), tracking radar(s), launcher(s), and countermeasure munitions. This technology is being postulated for the next generation of combat vehicles as well as a product improvement to existing vehicles. Active protection is believed to have a tremendous payoff by increasing the survivability of the ground combat vehicle without the burden of heavy armor. During combat, the components of the APS are subject to damage, which will degrade the performance of the APS. Using field data and engineering judgement, estimates of component damage from a single encounter are postulated for component packages of various sizes. This paper will answer the question: If an APS should last on average *k* rounds, then what size should the component package be?

INTRODUCTION

It is postulated that future ground combat vehicles will be much lighter than current ground combat vehicles. A consequence of this design trend is that armor, the traditional protection method, will only be a portion of the survivability solution for future ground combat vehicles. One of the techniques under both deployment and development, and the object of this paper, is that of an Active Protection System. It is postulated that an active protection system will reduce the need for armor. An AP system effects this reduction in armor by sensing an incoming threat, then tracking it, and at an appropriate time launching a counter-munition to intercept and destroy the incoming threat. Thus, the vehicles' armor need only deal with the residuals of the incoming threat, not the threat itself. There is, however, a fundamental difference between the protection afforded by traditional armor and that afforded by an AP system. Traditional armor is always effective (provided of course that one has enough of it), needs no action on the part of the user, and requires negligible amounts of maintenance. In contrast, an AP system may deplete its supply of countermunitions, or may suffer sufficient damage to one or more of its components that the system is rendered inoperable. The question that will be examined in this paper is the average length of operability for an AP system as a function of the survivability of its components.

STATEMENT OF THE PROBLEM

As indicated above, an AP system consists of various components: sensor(s), tracking radar(s), launcher(s), and countermunition. During battle these components are subject to damage, and damaged components will degrade the operability of the AP system so that it may be unable to meet its goal of vehicle protection. Component damage will alter the ability of the AP system to counter an incoming threat, but the lower the probabilities of component damage the longer the AP system can be expected to function effectively. The question this paper will address is: For a given level of component vulnerability, how long on average will the AP system continue to fully function.

BACKGROUND

The AP system considered in this paper is conceptually the same as the system considered in the paper *Functionality of Active Protection during Combat* by Caito, et al, [1]. Its four major subsystems, cueing sensors, tracking radar, launcher, and unguided countermunitions, are located outside of the vehicles armor envelope, and thus are subject to damage whenever the system encounters an ATGM.

The sequence of events when a functioning AP system engages a threat is as follows: The cueing sensor detects the launch of an ATGM and alerts the tracking radar. The tracking radar slews to the area of concern provided to it by the cueing sensor, and begins tracking the threat, sending data to a decision-making-module (not considered a component of the AP system, since it has other functions and is under armor). The decision-making-module determines the path of the incoming ATGM, and thereby determines an intercept point at some appropriate standoff distance from the vehicle and a counter-munition launch time. After launch the counter-munition intercepts the ATGM, disperses its load of steel balls, thereby providing a cloud of steels balls through which the ATGM must pass. This passage will cause the ATGM to detonate, breaking the jet into fragments by the time it reaches the vehicle. These fragments will still hit the vehicle the AP system is trying to protect, but will not penetrate it. The fragments, however, may result in damage to the components of the AP system. A reduction in component damage will result in increased AP system functionality, and it is the investigation of this connection that is the object of the current paper.

From [1], the surface area of the various AP system components are:

Cueing sensors (2 sensors)	50 in^2
Tracking radar	144 in^2
Launcher with rockets	225 in^2

The fragment data from [1] assumed that the AP system's countermunition predetonated the ATGM at a standoff distance of fifty meters. The same fragment data showed that approximately 110 fragments from the dispersed jet hit the vehicle. However, since it is reasonable to assume, as was done in [1], that the AP system components are mounted around the periphery of the vehicle, the number of fragments impacting the component areas of the AP system were in the 11 to 33 fragments range. The potential component mounting area of the AP system considered here is that area outside a one-sigma area of the aim-point, and it is estimated to have a presented area of 80 square-feet.

It is assumed that if a single fragment impacts a component of the AP system, then that component becomes non-functional. That is, a worse case scenario is assumed. Thus, from the data in the preceding paragraph, it is possible to compute the probabilities that a fragment will hit a cueing sensor, a tracking radar, or a launcher/countermunitions combination as a function of the number the fragments impacting the vehicle's presented potential component mounting area, that is, the area outside one-sigma of the aim-point. This computation is summarized in Table 1 below.

Table 1: Probabilities of component damage during an ATGM engagement

Number of fragments	Prob hit, sensor	Prob hit, radar	Prob hit, launcher
5	0.01	0.06	0.09
10	0.02	0.12	0.18
15	0.03	0.17	0.26
20	0.04	0.22	0.33
25	0.05	0.27	0.39
30	0.06	0.31	0.45
35	0.07	0.36	0.50

The hit probabilities given in Table 1 are driven by the number of fragments impacting the potential component mounting area of the vehicle, and by the surface area of the exposed AP components. In [1], using the data given above, a model of an AP system's functionality was created using the theory of Markov chains (For background information on Markov chains, please see Isaacson and Madsen, [2], or Kemeny and Snell, [3]). Assuming thirty-fragment encounters, that model showed that after six encounters the AP system would be non-functional. More alarming, the model showed that the average duration of an AP system's functionality was only 1.55 encounters, and against less taxing ten-fragment encounters, the model showed that the average duration of functionality for the AP system was 3.41 encounters.

The goal of this paper is to construct a Markov model of an AP system similar to the one constructed in [1] and to use the model backwards. That is, given an average number of encounters for which the AP system is desired to be functional, what size must the component package (sensors, radar, etc.) be in order to achieve that goal? This answer of course will depend upon the number of fragments assumed to have hit the potential component mounting area of the vehicle.

DAMAGE MODEL

In the model of an AP system constructed here, it will be assumed that if the tracking radar and the launcher are both functional, then the AP system is functional. This is not an especially restrictive assumption, since if the sensors are damaged the radar can be left on to scan and track. In summary, the AP system is regarded as functional if both the radar and launcher are functional, and non-functional otherwise. Thus, the model constructed, a Markov chain, will have only two states: functional (F), and non-functional (N). Since it's impossible to go from state N to state F (that is, N is an absorbing state), the model is completely specified when the transition probability from state F to state N is determined. This transition probability, p_{FN}, will of course depend upon the presented surface area of the tracking radar and of the launcher, as well as the number of fragments assumed to be impacting the potential component mounting area (the area outside of one-sigma of the aim-point) of the vehicle.

Let r and l be the presented surface areas, respectively, of the tracking radar and the launcher (in square feet). Given that the potential component mounting area is 80 square-feet, the probability of a single fragment hitting the radar or the launcher is $p_1 = (r + l)/80$. Thus, the probability of a single fragment missing the critical components (radar and launcher) is $1 - p_1 = 1 - (r + l)/80$. If k fragments are assumed, then the probability of all k fragments missing the radar and launcher is $(1 - (r + l)/80)^k$, so the probability of at least one hit upon a critical component will be $1 - (1 - (r + l)/80)^k$. That is,

$$p_{FN} = 1 - (1 - (r + l)/80)^k.$$

This value completely determines the model, and thus, the transition matrix of the Markov chain of the model. The transition matrix is

Table 2: Transition matrix for APS model, r. l, k variable

	F	N
F	$(1 - (r + l)/80)^k$	$1 - (1 - (r + l)/80)^k$
N	0	1

ANALYSIS OF APS FUNCTIONALITY

In the notional AP system described above, r had a value of 144 in^2 or 1 ft^2 and l had a value of 225 in^2 or 1.56 ft^2, so that $r + l$ had a value of 2.56 ft^2. Furthermore, again from data discussed above, the worse case scenario for the number of fragments impacting the component area was 35 fragments. With these values the AP system model is

Table 3: Transition matrix for APS model, $r = 1.00$, $l = 1.56$, $k = 35$

	F	N
F	.320	.680
N	0	1

From this the average number of encounters for which the AP system will be functional can be computed by

$$\sum_{k=1}^{\infty} k(.68)(.32)^{k-1}$$

However, from Markov theory, see [2] or [3], this number, that is, the average number of encounters for which the AP system will be functional, can also be computed from $1/(1 - p_{FF}) = 1/.68 = 1.47$. This is not a stellar performance.

Since the AP system designer has no control over the number of fragments impacting the component area of the vehicle, better AP system performance must be obtained by reducing the size of $r + l$. Let $u = r + l$. Then, since k, the number of fragments, has been set to 35, the transition matrix of the AP system model is

Table 4: Transition matrix for APS model, variable $u = r + l$, $k = 35$

	F	N
F	$(1 - u/80)^{35}$	$1 - (1 - u/80)^{35}$
N	0	1

Now, the notional AP system described above in the BACKGROUND section carries four countermunitions. Thus, an appropriate first step in improving the performance of this notional AP system would be to reduce u enough so that the average number of encounters for which the system will be functional is at least 4. From above, it's known that the average number of encounters is given by $1/(1 - p_{FF})$. It follows that what is needed is the u satisfying the equation

$$\frac{1}{1-(1-u/80)^{35}} = 4$$

This gives $u = .655$ ft^2.

A reduction in the presented surface area of the tracking radar and the launcher from the current 2.560 ft^2 to 0.655 ft^2 may be a reduction so severe that it will be impossible to achieve despite component miniaturization. However, with miniaturization and hardening it may be that not all of the 35 fragments under consideration will have sufficient energy to damage the AP components. Hence, below are presented the values of u, $u(k)$, corresponding to a variable number of fragments, k, that will provide the AP system an average of four functional encounters.

Table 5: AP system functionality for an average of four encounters

k, number of fragments	$u(k)$, component presented surface area
5	4.473
10	2.269
15	1.520
20	1.142
25	0.915
30	0.763
35	0.655

From this table it's seen that the current notional AP system (2.56 ft^2 of presented surface area) would be on average fully functional for four encounters provided the number of fragments striking the component area were somewhere between 5 and 10 fragments. Furthermore, from the table it's seen that with miniaturization and hardening, it would not be unreasonable to believe that an AP system could be designed that would have an average functionality of four encounters.

Averages, however, can be misleading, especially in the model of an AP system constructed here. The reason is that the model assumes in the computation of an average number of encounters that any number of encounters is possible, despite the fact that there can be at most four encounters (for the notional system considered). It follows that a better question to ask is this: If the AP system is required with high probability to be fully functional for four encounters, then what size of presented component surface area, u, is required to accomplish that requirement.

Recall that $p_{FF} = (1 - u/80)^k$ and $p_{FN} = 1 - p_{FF} = 1 - (1 - u/80)^k$, where k is the number of fragments and u is the combined surface area of the radar and launcher, in the transition matrix, T, of the model

Table 6: General transition matrix, T, for the AP system model

	F	N
F	p_{FF}	p_{FN}
N	0	1

Now, if the vector $v = [f, 1 - f]$ gives the probabilities of an AP system being functional, non-functional, respectively, before an encounter, then the vector

$$vT = [fp_{FF}, 1 - fp_{FF}]$$

gives the probabilities of the AP system being functional, non-functional after the encounter, or, what is the same, before the next encounter. This computation uses the fact that $p_{FN} = 1 - p_{FF}$. Likewise, $vT^2 = [fp_{FF}^2, 1 - fp_{FF}^2]$ provides the probabilities of the AP system being functional, non-functional after two encounters, and, in general, $vT^n = [fp_{FF}^n, 1 - fp_{FF}^n]$ gives the probabilities of the system being functional, non-functional after n encounters. For more details, please see either [2] or [3].

The question posed above can now be answered. The original functionality vector, v, can be taken to be [1, 0]. That is, the AP system is fully functional. The probability that the AP system will be functional at the beginning of the fourth encounter is, as just noted, p_{FF}^3, since in this instance $f = 1$. What is desired is that this value should be high, say .95. That is the AP system will be at least 95% functional for four encounters. Thus, it is required that $p_{FF}^3 \geq .95$. Since $p_{FF} = (1 - u/80)^k$, where k is the number of fragments, the inequality to solve, u in terms of k, is

$$(1 - u/80)^{3k} \geq .95$$

The solutions of the above inequality for presented surface area of the radar and launcher, u, in terms of the number of fragments, k, are given in the following table. These are the values that will provide for the AP system remaining functional through four encounters with a probability of 95%.

Table 7: u required for four-encounter functionality with probability .95

u (square feet)	k
.273	5
.137	10
.091	15
.068	20
.055	25
.046	30
.039	35

These are miniscule numbers. The most favorable five-fragment scenario allows only 40 square-inches for the presented surface area of both the radar and launcher. It's difficult to see how this can be achieved even with minimization and hardening.

CONCLUSION

Given the current standoff distance of fifty meters for intercepting an incoming ATGM, it will be extremely stressing to design an AP system that will remain functional for four encounters with high probability. The standoff distance will need to be increased, but an appropriate standoff distance has not been determined. In order to estimate a workable standoff distance, additional field-test data needs to be accumulated. Meanwhile, the minimization and hardening of AP system components needs to be aggressively pursued.

REFERENCES

[1] Caito, Steven, Daniel Hicks, William Jackson, and Jack Reed, *Functionality of Active Protection During Combat*, Proceedings of the Eleventh Annual Ground Vehicle Survivability Symposium, held at the Naval Postgraduate School, Monterey, California, 2000.

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[3] Kemeny, John G., and J. Laurie Snell, *Finite Markov Chains*, D. Van Nostrand Company, 1960.